Phases of nuclear matter and electroweak interactions within SM and beyond *

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We have performed a comprehensive study of the phase structure of cold, dilute nuclear matter featuring a S-D condensate at non-zero isospin asymmetry, within wide ranges of temperatures and densities. We find a rich phase diagram comprising three superfluid phases, namely a Larkin-Ovchinnikov-Fulde-Ferrell phase, the ordinary BCS phase, and a heterogeneous, phase-separated BCS phase, with associated crossovers from the latter two phases to a homogeneous or phase-separated Bose-Einstein condensate of deuterons. The phase diagram contains two tricritical points (one a Lifshitz point), which may degenerate into a single tetracritical point for some degree of isospin asymmetry. The formation of such isospin-asymmetric condensates is relevant to the astrophysical type-II supernovae and dilute tails of the heavy neutron-rich nuclei. Our model solves the Nozières–Schmitt-Rink equations for asymmetrical nuclear matter with a phase-shift equivalent (so-called realistic) interactions [1]. These results are shown in Fig. 1

Electroweak dynamics of baryons in dense matter has been studied within a formalism based on the re-summation of particle-hole ladders in bulk nuclear matter. As an application, the pair-breaking neutrino bremsstrahlung – an important process contributing to the neutrino cooling of a compact star – was computed. The vertex corrections substantially suppress the emission via vector currents, while they leave the axial vector emission unaffected. Neutrino emission rate from baryonic matter in neutron stars via weak neutral vector interaction was computed up to order $O(v_F^6)$, where v_F is the Fermi velocity in units of speed of light. The neutrino emissivity is enhanced compared to the result at $O(v_F^4)$ order up to 10% for values $v_F \leq 0.4$ characteristic to baryons in compact stars [2]. Although the next-to-leading correction is small, it provides a proof that the series expansion converges quickly and the leading order result is accurate to order 10%.

Once formed in a supernova explosion, a neutron star cools rapidly via neutrino emission during the first 10^4-10^5 yr of its life-time. Some extensions of the standard model (SM) invoke axions to solve several problems, including the strong CP problem of QCD and the nature of dark matter. We have computed the axion emission rate from baryonic components of a neutron star at temperatures below their respective critical temperatures T_c for normal-superfluid phase transition [3]. The axion production is driven by a charge neutral weak process, associated with Cooper pair breaking and recombination. The requirement that the axion cooling does not overshadow the neutrino cooling puts a lower bound on the axion decay constant $f_a > 6 \times 10^9\, T_{c9}^{-1}$ GeV, with $T_{c9} = T_c/10^9$ K. This translates into a upper bound on the axion mass $m_a < 10^{-3}\, T_{c9}$ eV.

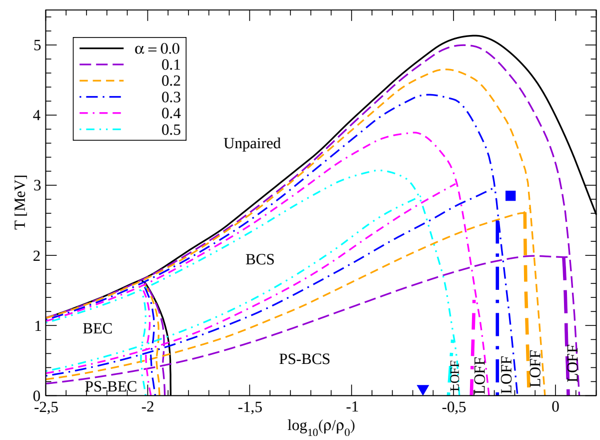

Figure 1: Phase diagram of dilute nuclear matter in the temperature-density plane for isospin asymmetries $\alpha = 0$ (solid, black online), 0.1 (dashed), 0.2 (short-dashed), 0.3 (dash-dotted), 0.4 (double-dash-dotted), and 0.5 (dash-double-dotted). Included are four phases: unpaired, BCS (BEC), LOFF, and PS-BCS (PS-BEC). For each asymmetry there are two tri-critical points, one of which is always a Lifshitz point. For special values of asymmetry these two points degenerate into a single tetracritical point at $\log_{10}(\rho/\rho_0) = -0.22$ and $T = 2.85$ MeV (shown by a square dot) for $\alpha_4 = 0.255$. The LOFF phase disappears at the point $\log_{10}(\rho/\rho_0) = -0.65$ and $T = 0$ (shown by a triangle) for $\alpha = 0.62$. The density-temperature strips where the LOFF phase is the ground state are marked, for each asymmetry, by "LOFF".

References

[1] M. Stein, X. -G. Huang, A. Sedrakian and J. W. Clark, *Phase diagram of dilute nuclear matter: Unconventional pairing and the BCS-BEC crossover.* Phys. Rev. C **86**, 062801(R) (2012).

[2] A. Sedrakian, *Vertex renormalization of weak interactions in compact stars: beyond leading order*. Phys. Rev. C **86**, 025803 (2012).

[3] J. Keller and A. Sedrakian, *Axions from cooling compact stars: pair-breaking processes.* Nuclear Physics A **897**, 62 (2013).

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